OPTIMUM REFUELING FOR HELICOPTER LOGGING: A MODEL

David F. Gibson

USDA Forest Service General Technical Report INT-15, 1974
INTERMOUNTAIN FOREST & RANGE
EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

DAVID F. GIBSON is Associate Professor, Industrial and Management Engineering, Montana State University. For the past 2 years, he has been working cooperatively with the Intermountain Station's Forest Engineering Research Unit at Bozeman as a Research Industrial Engineer under the Intergovernmental Personnel Act. He holds B.S., M.S., and Ph.D. degrees in Industrial Engineering from Purdue University.

USDA Forest Service
General Technical Report INT-15
August 1974

OPTIMUM REFUELING FOR HELICOPTER LOGGING: A MODEL

David F. Gibson

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

CONTENTS

ABSTRACT

Effectiveness of a helicopter logging system, as measured by pounds of logs yarded or profit per day, is influenced by the amount of fuel carried by the aircraft. A cost model and computer program (FORTRAN IV) are presented that determine the optimum amount of fuel to carry for parameters of the operating system. The model can also be employed to assess effects of changes in parameters on the productivity of the system. The model can be used to establish a benchmark by which actual production can be predicted and monitored.

KEYWORDS: helicopter logging, optimization, refueling.

INTRODUCTION

Increased awareness of the environmental impact of logging has stimulated interest in yarding by means of helicopters. In addition, the great demand for wood products has made helicopter logging an attractive technique for harvesting timber heretofore inaccessible.

In recent years, the number of timber sales devoted exclusively to helicopter yarding has increased so dramatically that helicopter yarding is no longer in the experimental stages--its practicality has been established. Although approximately 20 helicopters are in use in logging operations today, helicopter yarding remains an expensive proposition. Stevens (1972, 1973) and Binkley (1972) have reported on various cost, production, and equipment capability aspects of helicopter logging.

The Intermountain Forest and Range Experiment Station at Bozeman, Montana, has been engaged in such an effort to improve the cost effectiveness of helicopter logging as part of a comprehensive study of advanced logging systems. This paper presents an optimum refueling model for helicopter logging. Given parameters within which the helicopter will operate, the model determines the optimum amount of fuel that the aircraft should carry and the resulting operating characteristics of the system. Potential improvements in production depend upon parameters of the system, but may generally be expected to vary about 10 percent within current operating ranges.

PROBLEM DEFINITION

The rationale behind the model is that every pound of fuel carried displaces a pound of payload. The more fuel the aircraft carries the longer it can operate before refueling, but also the smaller the average payload per turn. Thus a cost model that maximizes profit (or equivalently pounds yarded) over a given period of time is defined. The amount of fuel carried by the ship is treated as a variable. This is expressed as:

Z = value of timber yarded - costs incurred
= value of timber yarded - (total average cycle cost + cost to refuel + cost to travel to and from refueling + cost while system down).

MODEL CONSTRUCTION

Definitions of Terms

Terms used in the model are:

A = average fuel consumption rate (gal/min)
ADLR = average distance from landing to refueling point (ft)
ADLW = average distance from landing to woods (ft)
ADRW = average distance from refueling point to woods (ft)
AHT = average hooking time (min)
AVP = average payload per turn (lb)
C = amount of fuel carried (gal)
DTC = downtime cost ($/min)
F = fuel capacity of helicopter (gal)
FLF = flight load factor (average fraction of maximum load carried)
FDT = fraction of workday system down
OC = system operating cost while yarding ($/min)
P = payload of helicopter at full fuel (lb)
PUHT = average positioning and unhooking time (min)
RFC = refueling cost ($/min)
RFLT = reserve flight time (min)
SI = speed toward landing (ft/min)
SO = speed out to woods (ft/min)
TRF = time to refuel (min)
V = value of timber yarded ($/lb)
W = weight of fuel (lb/gal)
XL = length of workday (min)

Development of Equation

Each component of the cost equation is now defined using the terms given above.

A. Value of timber yarded

value of timber yarded per workday = (number of loads yarded per workday) × (average payload per turn) × (value of timber yarded).

(1) number of loads yarded per workday = N1 + NRF

The first term (N1) accounts for round trips from the woods to the landing and back; the second term (NRF) allows for the last trip from the woods to the landing before returning to refuel.

$$N1 = \frac{(XL - XL \cdot FDT) - NRF\left[TRF + \left(\frac{ADLR+ADRW}{SO}\right) + \left(\frac{ADLW}{SI} + AHT + PUHT\right)\right]}{\left[\left(\frac{SI + SO}{SI \cdot SO}\right) ADLW + AHT + PUHT\right]}$$

$$NRF = \frac{(XL - XL \cdot FDT) \cdot A}{C + TRF \cdot A}$$

(2) average payload per turn

The model is constructed to consider two alternative evaluations relative to payload:

(a) Theoretical average payload (AVP_t)

Conceptually, on each successive turn, the helicopter will be able to yard a greater payload since it is carrying less fuel. If loads were constructed to take advantage of this situation (it is approached when yarding material such as cement on construction projects), the average payload yarded would be:

$$\begin{aligned} AVP_t = FLF \cdot \{&[P + (F - C)\,W - \left(\frac{RFLT}{A}\right) W] \\ &+ [A \cdot W\,(ADRW \cdot SO^{-1} + AHT) \\ &+ .5(N-1) \cdot A \cdot W\,(ADLW\,\left(\frac{SI + SO}{SI \cdot SO}\right) \\ &+ AHT + PUHT)]\} \end{aligned}$$

where N is the number of loads yarded between refuelings.

$$N = \frac{[C - \left(\frac{ADLR+ADRW}{SO}\right)A - \left(\frac{ADLW}{SI} + AHT + PUHT\right)A] + [ADLW\,\left(\frac{SI+SO}{SI \cdot SO}\right) + AHT + PUHT]A}{[ADLW\,\left(\frac{SI+SO}{SI \cdot SO}\right) + AHT + PUHT]A}$$

The second term in [ ] in the expression for AVP_t relates to conceptually being able to add a pound of timber for each pound of fuel consumed. It should be noted AVP_t is maximized when the flight load factor, FLF, is 1 and the reserve flight time, RFLT, is 0.

(b) actual average payload (AVP_a)

The expression for the actual average payload can be obtained by omitting the second term in [ ] in the expression for AVP_t.

$$AVP_a = FLF\ [P + (F - C)\ W - (\frac{RFLT}{A})\ W]$$

B. Total average cycle cost per workday (TACC)

$$TACC = N1\ [(\frac{SI + SO}{SI \cdot SO})\ ADLW + AHT + PUHT]\ OC$$

$$+ NRF\ (\frac{ADLW}{SI} + AHT + PUHT)\ OC$$

C. Cost to refuel per workday (CRF)

$$CRF = TRF \cdot RFC \cdot NRF$$

D. Cost to travel to and from refueling per workday (CTTR)

$$CTTR = NRF\ (\frac{ADLR + ADRW}{SO})\ OC$$

E. Cost while system down per workday (CSD)

$$CSD = FDT \cdot XL \cdot DTC$$

OPTIMIZATION

To find that value of C (the amount of fuel carried) that maximizes

$$Z = (N1 + NRF)\ AVP \cdot V - [TACC + CRF + CTTR + CSD],$$

we must differentiate with respect to C, set it equal to 0, and then solve for C. Differentiating the equation with respect to C and setting it equal to 0 results in an expression of the form

$$\alpha C^2 + \beta C + \gamma = 0$$

which is recognized as a quadratic equation with the solution

$$C = \frac{-\beta \pm (\beta^2 - 4 \cdot \alpha \cdot \gamma)^{\frac{1}{2}}}{2 \cdot \alpha}$$

α, β, and γ are constants involving the parameters of the system and are given below.

$$\alpha = \frac{W\ (.5A - 1)\ (XL - XL \cdot FDT)\ SI \cdot SO \cdot V}{(SI + SO)\ ADLW + AHT \cdot SI \cdot SO + PUHT \cdot SI \cdot SO}$$

$$\beta = \frac{2W\ (.5A - 1)\ (XL - XL \cdot FDT)\ SI \cdot SO \cdot V \cdot A \cdot TRF}{(SI + SO)\ ADLW + AHT \cdot SI \cdot SO + PUHT \cdot SI \cdot SO}$$

$$\begin{aligned}\gamma = {} & (A \cdot TRF)\ [XK5 \cdot XK3 \cdot V - XK7 \cdot XK4 \cdot V \\ & + (XL - XL \cdot FDT)\ A \cdot XK4 \cdot V - XK5 \cdot XK9] \\ & - [XK7 \cdot XK9 + (XL - XL \cdot FDT)\ A \cdot XK3 \cdot V \\ & - XK7 \cdot XK3 \cdot V - XK10]\end{aligned}$$

Computational variables used to express γ above are defined in table 1.

Table 1.--*Definitions of computational variables.*

$$XK5 = \frac{(XL - XL \cdot FDT)\ SI \cdot SO}{[(SI + SO)\ ADLW + AHT \cdot SI \cdot SO + PUHT \cdot SI \cdot SO]}$$

$$XK7 = \frac{[(XL-XL \cdot FDT)A]\ SI(ADLR+ADRW) + [(XL-XL \cdot FDT)A]\ [ADLW \cdot SO+AHT \cdot SI \cdot SO+PUHT \cdot SI \cdot SO]}{[(SI + SO)\ ADLW + AHT \cdot SI \cdot SO + PUHT \cdot SI \cdot SO]}$$

$$XK9 = [(\frac{SI + SO}{SI \cdot SO})\ ADLW + AHT + PUHT]\ OC$$

$$XK10 = (XL - XL \cdot FDT)\ A[(\frac{ADLW}{SI} + AHT + PUHT)\ OC + TRF \cdot RFC + (\frac{ADLR+ADRW}{SO})\ OC]$$

XK3 and XK4 are defined below in two cases, $XK3_a$, $XK4_a$ and $XK3_t$, $XK4_t$, depending upon whether AVP_a or AVP_t is being considered, respectively.

$$XK3_a = FLF\ [P + (F - \frac{RFLT}{A})\ W]$$

$$XK4_a = - FLF \cdot W$$

$$XK3_t = FLF\ \{[P + (F - \frac{RFLT}{A})\ W] + [\frac{-XK1 \cdot XK2}{XK1P} - XK2 + A \cdot W\ (ADRW \cdot SO^{-1} + AHT)]\}$$

$$XK4_t = \frac{XK2}{XK1P} - W$$

where

$$XK1 = A\ \{(\frac{ADLR + ADRW}{SO}) + (\frac{ADLW}{SI} + AHT + PUHT) - [ADLW\ (\frac{SI + SO}{SI \cdot SO}) + AHT + PUHT]\}$$

$$XK2 = .5A \cdot W\ [ADLW\ (\frac{SI + SO}{SI \cdot SO}) + AHT + PUHT]$$

$$XK1P = A\ [ADLW\ (\frac{SI + SO}{SI \cdot SO}) + AHT + PUHT]$$

COMPUTER PROGRAM

The computer program that calculates the optimum refueling amount together with the resulting system operating characteristics is available on request as a listing from the Forestry Sciences Laboratory, Bozeman, Montana 59715 (Attn: David F. Gibson). The program is written in FORTRAN IV. Input and output are designed for use of either a teletype terminal or a line printer. Examples illustrating alternative evaluations and use of the program are given in the next section.

Input to the program is as follows. On the first data card, or line on a terminal, eight variables are read with a format of F10.4 each. These variables are, in order, as follows.

- SI - Helicopter speed toward the landing expressed in feet per minute. This represents the average speed of the aircraft when yarding.
- SO - Helicopter speed out from landing expressed in feet per minute. This represents the average speed of the helicopter when it is not yarding, such as when returning to the woods and traveling to the refueling point.
- ADLR - Average distance from the landing to the refueling point expressed in feet.
- ADRW - Average distance from the refueling point to the woods expressed in feet.
- ADLW - Average distance from the landing to the woods expressed in feet. This represents the average yarding distance.
- A - Average fuel consumption rate of the aircraft expressed in gallons per minute.
- W - Weight of fuel used by the aircraft expressed in pounds per gallon.
- XL - Length of workday expressed in minutes.

The second data card of input, or line on a terminal, contains seven fields, the first six of which have a format of F10.4 and the last one having a format of I1.

RFC - Refueling cost expressed in dollars per minute. This is the cost of operating the entire helicopter logging system when the aircraft is being refueled.
P - Payload of the helicopter expressed in pounds when it is carrying a full load of fuel.
F - Fuel capacity of the helicopter expressed in gallons.
V - Value of the timber yarded expressed in dollars per pound.
AHT - Average hooking time expressed in minutes. This time also includes the time required to position the helicopter over the load prior to hooking.
FDT - Fraction of downtime expressed as a decimal. It represents the portion of the workday that the helicopter will be down for reasons other than refueling.

IGR - A control variable for the program. Enter a 0 if no graphical output is desired. Enter a 1 if a graph of weight yarded per workday versus refueling amount is desired. Enter a 2 if a graph of profit per workday versus refueling amount is desired. Enter a 3 if graphs of both weight and profit per workday versus refueling amount are desired. Flight time between refuelings is also given on the graphs.

Information entered on the third data card also contains seven fields, the first six of which have a format of F10.4 and the last has a format of I1.

OC - Operating cost of the system expressed in dollars per minute. This is the cost of the entire helicopter logging system while timber is being yarded by the aircraft.

TRF - Average time to refuel the aircraft expressed in minutes. This does not include the time required to travel to the refueling point or the time required to return to the woods.

PUHT - Average positioning and unhooking time expressed in minutes. This includes the time required to lift the hooked timber clear of standing trees, position over the landing, and release the load.

RFLT - Reserve flight time expressed in minutes. This represents the amount of flight time that is desired to be maintained in reserve as a safety measure.

FLF - Flight load factor expressed as a decimal. This represents the anticipated fraction of total lifting capacity of the aircraft that will be realized by the average load. For example, if it is anticipated that 70 percent of the aircraft's lifting capacity will be realized, on the average, for loads yarded, then an entry of 0.70 is made.

DTC - Downtime cost as expressed in dollars per minute. This is the cost of the entire helicopter logging system when the aircraft is down for reasons other than refueling.

KEY - This is another control variable for the program. If calculations are to be made considering AVP_a (explained in previous section), then a 0 or no entry is made. However, if calculations are to be made considering AVP_t (explained in previous section), a 1 is entered.

EXAMPLES

Five examples are presented to illustrate the use of the model. These are contrived examples. Their data (table 2) were not obtained from actual operations.

Table 2.--*Computer inputs for examples of helicopter logging*

Input variable	Example				
	I	II	III	IV	V
SI	3000.	3000.	3000.	3000.	3000.
SO	4000.	4000.	4000.	4000.	4000.
ADLR	2000.	2000.	2000.	2000.	0
ADRW	4800.	4800.	4800.	4800.	4000.
ADLW	4000.	4000.	4000.	4000.	4000.
A	3.5	3.5	3.5	3.5	3.5
W	6.5	6.5	6.5	6.5	6.5
XL	480.	480.	480.	480.	480.
RFC	8.	8.	8.	8.	8.
P	8000.	8000.	8000.	8000.	8000.
F	1000.	1000.	1000.	1000.	1000.
V	.015	.015	.015	.015	.015
AHT	2.0	2.0	2.0	2.0	2.0
FDT	.10	.00	.00	.00	.10
IGR	0	0	0	0	3.
OC	14.	14.	14.	14.	14.
TRF	8.	8.	8.	8.	8.
PUHT	.25	.25	.25	.25	.25
RFLT	10.	10.	10.	10.	10.
FLF	.70	.70	1.0	1.0	.70
DTC	8.	8.	8.	8.	8.
KEY	0	0	0	1.	0

Figures 1, 2, 3, and 4 show the computer output for examples I, II, III, and IV, respectively. Because the input variable IGR was set equal to 0 in these four examples, no graphical output resulted. Integers representing system characteristics have been rounded down. The productivity of the system increases successively from examples I to IV. The system represented in example II is more productive than the system in example I because the fraction of downtime (as input via variable FDT) decreases from 0.10 to 0.00 (all other inputs remained the same). Example III shows an increase in productivity over example II because the flight load factor (FLF) is increased from 0.70 to 1.0 while all other inputs remained unchanged. The system represented in example IV is more productive than that in example III, because AVP_t is considered instead of AVP_a. This is accomplished by setting the input variable KEY equal to 1.

```
HELICOPTER LOGGING ANALYSIS
OPTIMUM REFUELING MODEL

SYSTEM PARAMETERS

SPEED IN =  3000.0 FT/MIN    SPEED OUT =  4000.0 FT/MIN
AVERAGE YARDING DISTANCE =  4000.0 FT
DISTANCE FROM LANDING TO REFUELING POINT =  2000.0 FT
AVERAGE DISTANCE FROM REFUELING POINT TO WOODS =  4800.0 FT
WORK DAY =  480.0 MIN    SYSTEM OPERATING COST =  14.0 $/MIN
FRACTION DOWNTIME =  .10    DOWNTIME COST =   8.0 $/MIN
PAYLOAD (FULL FUEL) =  8000.0 LB
FLIGHT LOAD FACTOR =  .70    REFUELING COST =   8.0 $/MIN
MAX FUEL CAPACITY =  1000.0 GAL
FUEL CONSUMPTION RATE =  3.5 GAL/MIN
RESERVE FLIGHT TIME =  10.0 MIN    TIME TO REFUEL =  8.0 MIN
AVERAGE HOOKING TIME =  2.0 MIN    TIMBER VALUE =  .015 $/LB
POSITION & UNHOOKING TIME =  .25 MIN

SYSTEM OPERATING CHARACTERISTICS

REFUELING AMOUNT =   211.60  GAL     TURNS PER DAY =   82
TURNS BETWEEN REFUELING =   13
FLIGHT TIME BETWEEN REFUELING =   60.5  MIN
NUMBER OF REFUELINGS PER DAY =   6
PERCENT YARDING TIME =  77.2
PERCENT REFUELING TIME =  12.8
PERCENT DOWNTIME =  10.0
PROFIT PER DAY =  $   5193.18
WEIGHT OF TIMBER YARDED PER DAY =     754817.63  LB
```

Figure 1.--Example I computer output.

```
HELICOPTER LOGGING ANALYSIS
OPTIMUM REFUELING MODEL

SYSTEM PARAMETERS

SPEED IN =  3000.0 FT/MIN    SPEED OUT =  4000.0 FT/MIN
AVERAGE YARDING DISTANCE =  4000.0 FT
DISTANCE FROM LANDING TO REFUELING POINT =  2000.0 FT
AVERAGE DISTANCE FROM REFUELING POINT TO WOODS =  4800.0 FT
WORK DAY =  480.0 MIN    SYSTEM OPERATING COST =  14.0 $/MIN
FRACTION DOWNTIME =  .00    DOWNTIME COST =   8.0 $/MIN
PAYLOAD (FULL FUEL) =  8000.0 LB
FLIGHT LOAD FACTOR =  .70    REFUELING COST =   8.0 $/MIN
MAX FUEL CAPACITY =  1000.0 GAL
FUEL CONSUMPTION RATE =  3.5 GAL/MIN
RESERVE FLIGHT TIME =  10.0 MIN    TIME TO REFUEL =  8.0 MIN
AVERAGE HOOKING TIME =  2.0 MIN    TIMBER VALUE =  .015 $/LB
POSITION & UNHOOKING TIME =  .25 MIN

SYSTEM OPERATING CHARACTERISTICS

REFUELING AMOUNT =   211.60  GAL     TURNS PER DAY =   91
TURNS BETWEEN REFUELING =   13
FLIGHT TIME BETWEEN REFUELING =   60.5  MIN
NUMBER OF REFUELINGS PER DAY =   7
PERCENT YARDING TIME =  85.8
PERCENT REFUELING TIME =  14.2
PERCENT DOWNTIME =   .0
PROFIT PER DAY =  $   6196.85
WEIGHT OF TIMBER YARDED PER DAY =     838686.69  LB
```

Figure 2.--Example II computer output.

```
HELICOPTER LOGGING ANALYSIS
OPTIMUM REFUELING MODEL

SYSTEM PARAMETERS

SPEED IN =  3000.0 FT/MIN    SPEED OUT =  4000.0 FT/MIN
AVERAGE YARDING DISTANCE =  4000.0 FT
DISTANCE FROM LANDING TO REFUELING POINT =  2000.0 FT
AVERAGE DISTANCE FROM REFUELING POINT TO WOODS =  4800.0 FT
WORK DAY =  480.0 MIN    SYSTEM OPERATING COST =  14.0 $/MIN
FRACTION DOWNTIME =  .00    DOWNTIME COST =   8.0 $/MIN
PAYLOAD (FULL FUEL) =  8000.0 LB
FLIGHT LOAD FACTOR = 1.00    REFUELING COST =   8.0 $/MIN
MAX FUEL CAPACITY =  1000.0 GAL
FUEL CONSUMPTION RATE =  3.5 GAL/MIN
RESERVE FLIGHT TIME =  10.0 MIN    TIME TO REFUEL =  8.0 MIN
AVERAGE HOOKING TIME =  2.0 MIN    TIMBER VALUE =  .015 $/LB
POSITION & UNHOOKING TIME =  .25 MIN

SYSTEM OPERATING CHARACTERISTICS

REFUELING AMOUNT =   218.57  GAL     TURNS PER DAY =   91
TURNS BETWEEN REFUELING =   13
FLIGHT TIME BETWEEN REFUELING =   62.4  MIN
NUMBER OF REFUELINGS PER DAY =   6
PERCENT YARDING TIME =  86.2
PERCENT REFUELING TIME =  13.8
PERCENT DOWNTIME =    .0
PROFIT PER DAY =  $  11590.49
WEIGHT OF TIMBER YARDED PER DAY =    1198894.00  LB
```

Figure 3.--Example III computer output.

```
HELICOPTER LOGGING ANALYSIS
OPTIMUM REFUELING MODEL

SYSTEM PARAMETERS

SPEED IN =  3000.0 FT/MIN    SPEED OUT =  4000.0 FT/MIN
AVERAGE YARDING DISTANCE =  4000.0 FT
DISTANCE FROM LANDING TO REFUELING POINT =  2000.0 FT
AVERAGE DISTANCE FROM REFUELING POINT TO WOODS =  4800.0 FT
WORK DAY =  480.0 MIN    SYSTEM OPERATING COST =  14.0 $/MIN
FRACTION DOWNTIME =  .00    DOWNTIME COST =   8.0 $/MIN
PAYLOAD (FULL FUEL) =  8000.0 LB
FLIGHT LOAD FACTOR = 1.00    REFUELING COST =   8.0 $/MIN
MAX FUEL CAPACITY =  1000.0 GAL
FUEL CONSUMPTION RATE =  3.5 GAL/MIN
RESERVE FLIGHT TIME =  10.0 MIN    TIME TO REFUEL =  8.0 MIN
AVERAGE HOOKING TIME =  2.0 MIN    TIMBER VALUE =  .015 $/LB
POSITION & UNHOOKING TIME =  .25 MIN

SYSTEM OPERATING CHARACTERISTICS

REFUELING AMOUNT =   319.01  GAL     TURNS PER DAY =   95
TURNS BETWEEN REFUELING =   19
FLIGHT TIME BETWEEN REFUELING =   91.1  MIN
NUMBER OF REFUELINGS PER DAY =   4
PERCENT YARDING TIME =  90.2
PERCENT REFUELING TIME =   9.8
PERCENT DOWNTIME =    .0
PROFIT PER DAY =  $  12730.22
WEIGHT OF TIMBER YARDED PER DAY =    1281188.00  LB
```

Figure 4.--Example IV computer output.

Table 3.--*Summary of computer output for examples of helicopter logging*

	Example				
	I	II	III	IV	V
Refueling amount (gal)	212	212	219	319	200
Turns per day	82	91	91	95	82
Turns between refuelings	13	13	13	19	12
Flight time between refuelings (min)	61	61	62	91	57
Number of refuelings per day	6	7	6	4	6
Percent yarding time	77	86	86	90	78
Percent refueling time	13	14	14	10	12
Percent downtime	10	0	0	0	10
Profit per day ($)	5,193	6,197	11,590	12,730	5,330
Weight of timber yarded per day (lb)	754,818	838,687	1,198,894	1,281,188	762,862

Graphs of C (refueling amount) versus weight yarded and profit per workday are given by figures 5 and 6, respectively, for examples I through IV. Each line on the graphs is designated by the appropriate example number. The increase in productivity mentioned previously can also be discerned on these graphs. It can be seen that the curves are fairly flat in the region near optimality, but it is more costly to "underfuel" than to "overfuel" the aircraft. Note that figures 5 and 6 were not obtained from the program, but resulted from running a similar program on a CALCOMP plotter. The program described is designed for output on a teletype or a line printer because these modes of output are commonly available.

Figure 7 illustrates the graphical output of the program for example V. This example has the same input as example I except for ADLR, ADRW, and IGR. To illustrate the effect of locating the refueling point at the landing, ADLR was set equal to 0 and ADRW was set equal to ADLW. Also, to obtain graphs of both weight yarded and profit per workday versus amount of refueling, the input variable IGR was set equal to 3. Table 3 summarizes the output of the five examples.

An illustration of the many alternative evaluations available to the user follows. Assume that the system being evaluated is characterized by the input data of example V and hence the results are as given in figure 7. Suppose, however, that the flight time between refueling cannot be 57 minutes as optimally prescribed, but must be 40 minutes. This latter time is located on the graphs, and the gallons to be refueled, the weight yarded, and the profit per workday are approximated at 140 gallons, 746,000 pounds, and $5,190, respectively.

If an evaluation is to be accomplished where the helicopter remains running during refueling, the following consideration should be made. Fuel burned during refueling is considered to be obtained from the reserve flight time and should be added to the prescribed amount C to obtain the total refueling amount. As shown by figure 8, the amount that should be refueled is c + d, that is, the prescribed amount plus the amount burned during refueling.

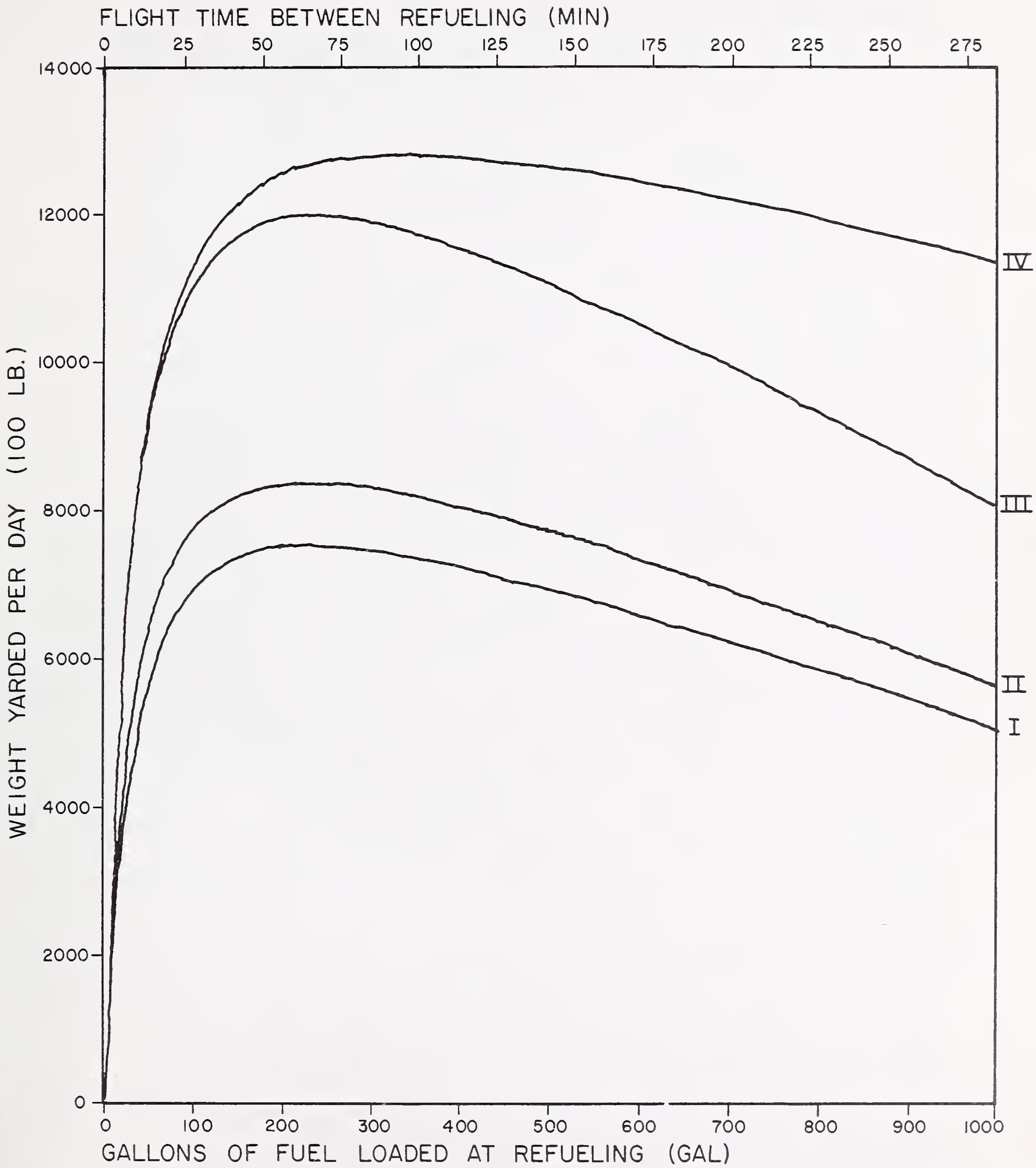


Figure 5.--Weight yarded per workday versus refueling amount for examples I, II, III, and IV.

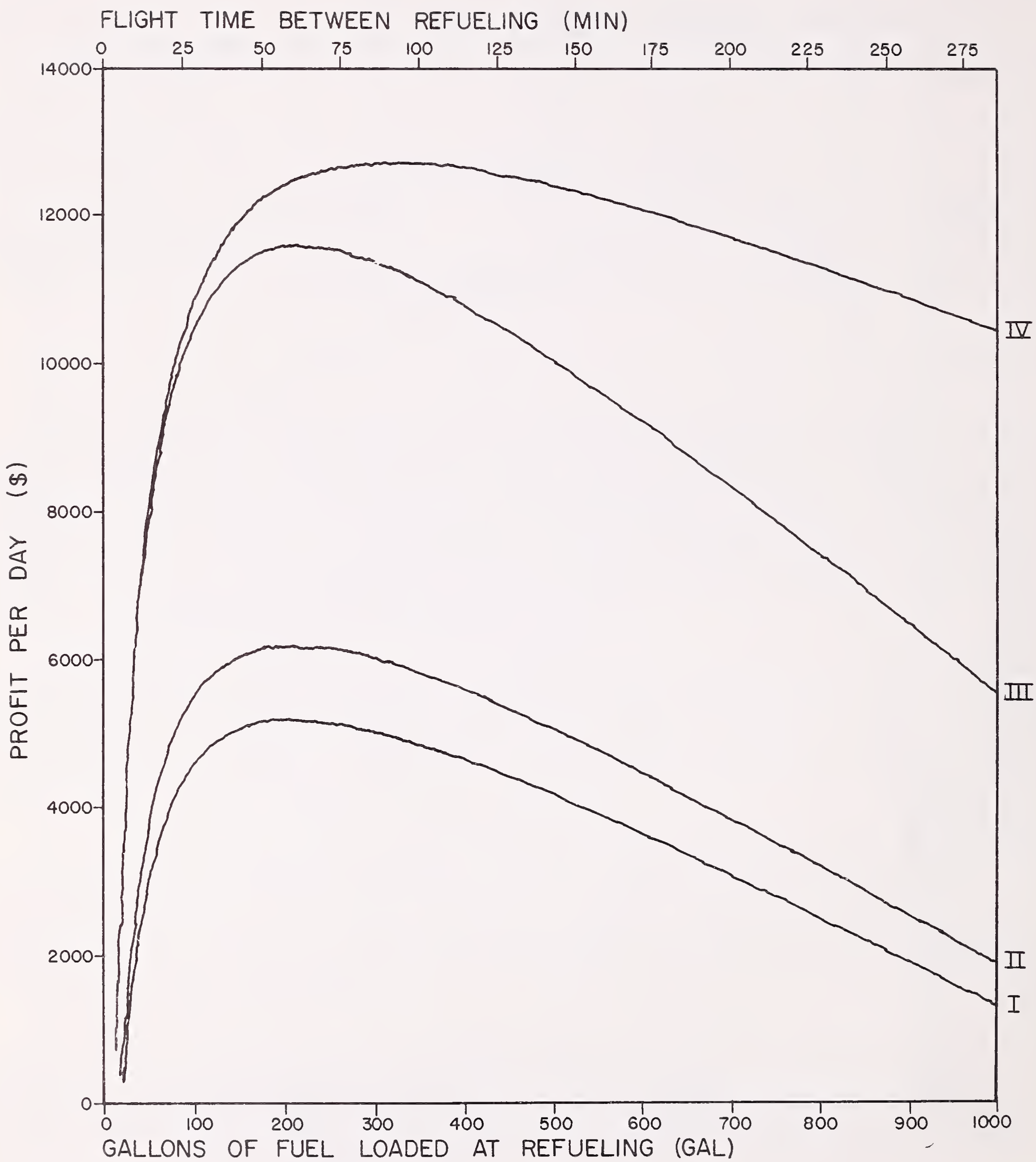
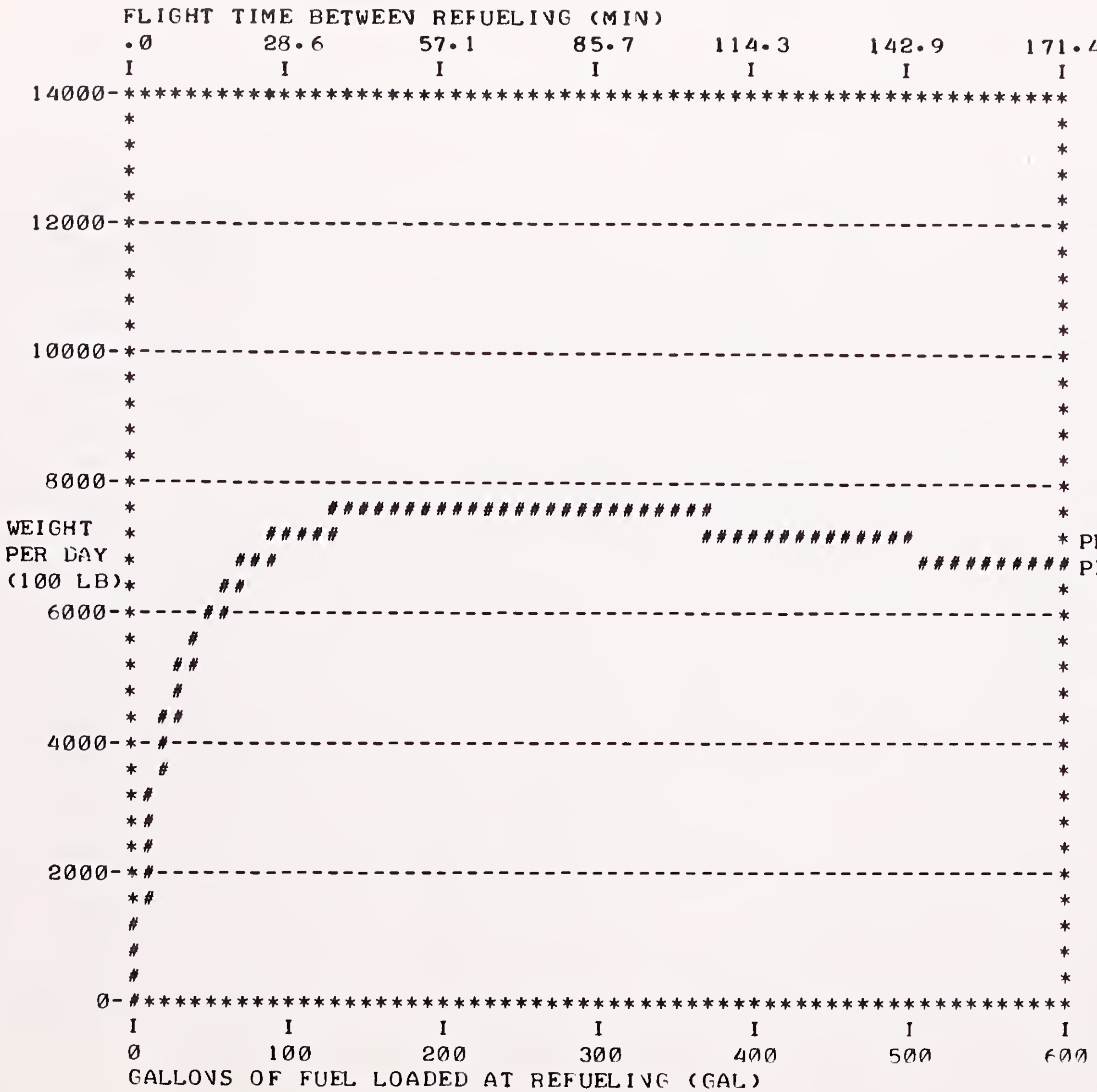


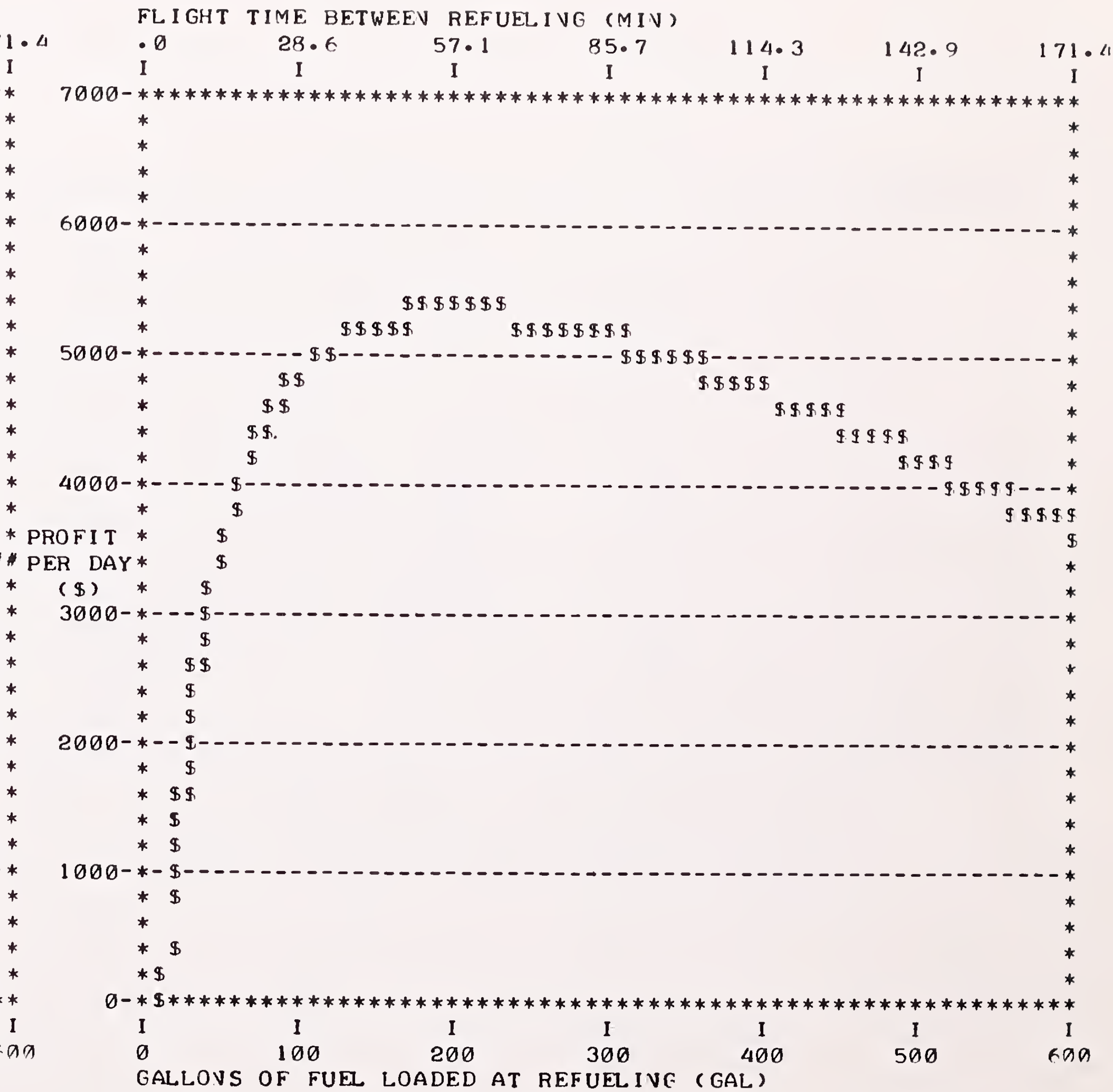
Figure 6.--Profit per workday versus refueling amount for examples I, II, III, and IV.

Figure 7.--Example V computer output.

```
HELICOPTER LOGGING ANALYSIS

OPTIMUM REFUELING MODEL

SYSTEM PARAMETERS

SPEED IN =  3000.0 FT/MIN     SPEED OUT =  4000.0 FT/MIN

AVERAGE YARDING DISTANCE =  4000.0 FT

DISTANCE FROM LANDING TO REFUELING POINT =       .0 FT

AVERAGE DISTANCE FROM REFUELING POINT TO WOODS =  4000.0 FT

WORK DAY =  480.0 MIN     SYSTEM OPERATING COST =  14.0 $/MIN

FRACTION DOWNTIME =  .10     DOWNTIME COST =   8.0 $/MIN

PAYLOAD (FULL FUEL) =  8000.0 LB

FLIGHT LOAD FACTOR =  .70     REFUELING COST =   8.0 $/MIN

MAX FUEL CAPACITY =  1000.0 GAL

FUEL CONSUMPTION RATE =  3.5 GAL/MIN

RESERVE FLIGHT TIME =  10.0 MIN     TIME TO REFUEL =  8.0 MIN

AVERAGE HOOKING TIME =  2.0 MIN     TIMBER VALUE =  .015 $/LB

POSITION & UNHOOKING TIME =  .25 MIN


SYSTEM OPERATING CHARACTERISTICS

REFUELING AMOUNT =   199.78  GAL     TURNS PER DAY =   82

TURNS BETWEEN REFUELING =   12

FLIGHT TIME BETWEEN REFUELING =   57.1  MIN

NUMBER OF REFUELINGS PER DAY =   6

PERCENT YARDING TIME =  77.6

PERCENT REFUELING TIME =  12.4

PERCENT DOWNTIME =  10.0

PROFIT PER DAY =  $   5329.56

WEIGHT OF TIMBER YARDED PER DAY =     762861.56  LB
```


(Con. next page)


FLIGHT TIME BETWEEN REFUELING (MIN)
.0 28.6 57.1 85.7 114.3 142.9 171.4
14000
12000
10000
8000
6000
4000
2000
0
WEIGHT PER DAY (100 LB)
0 100 200 300 400 500 600
GALLONS OF FUEL LOADED AT REFUELING (GAL)


FLIGHT TIME BETWEEN REFUELING (MIN)
.0 28.6 57.1 85.7 114.3 142.9 171.4
7000
6000
5000
4000
3000
2000
1000
0
PROFIT PER DAY ($)
0 100 200 300 400 500 600
GALLONS OF FUEL LOADED AT REFUELING (GAL)

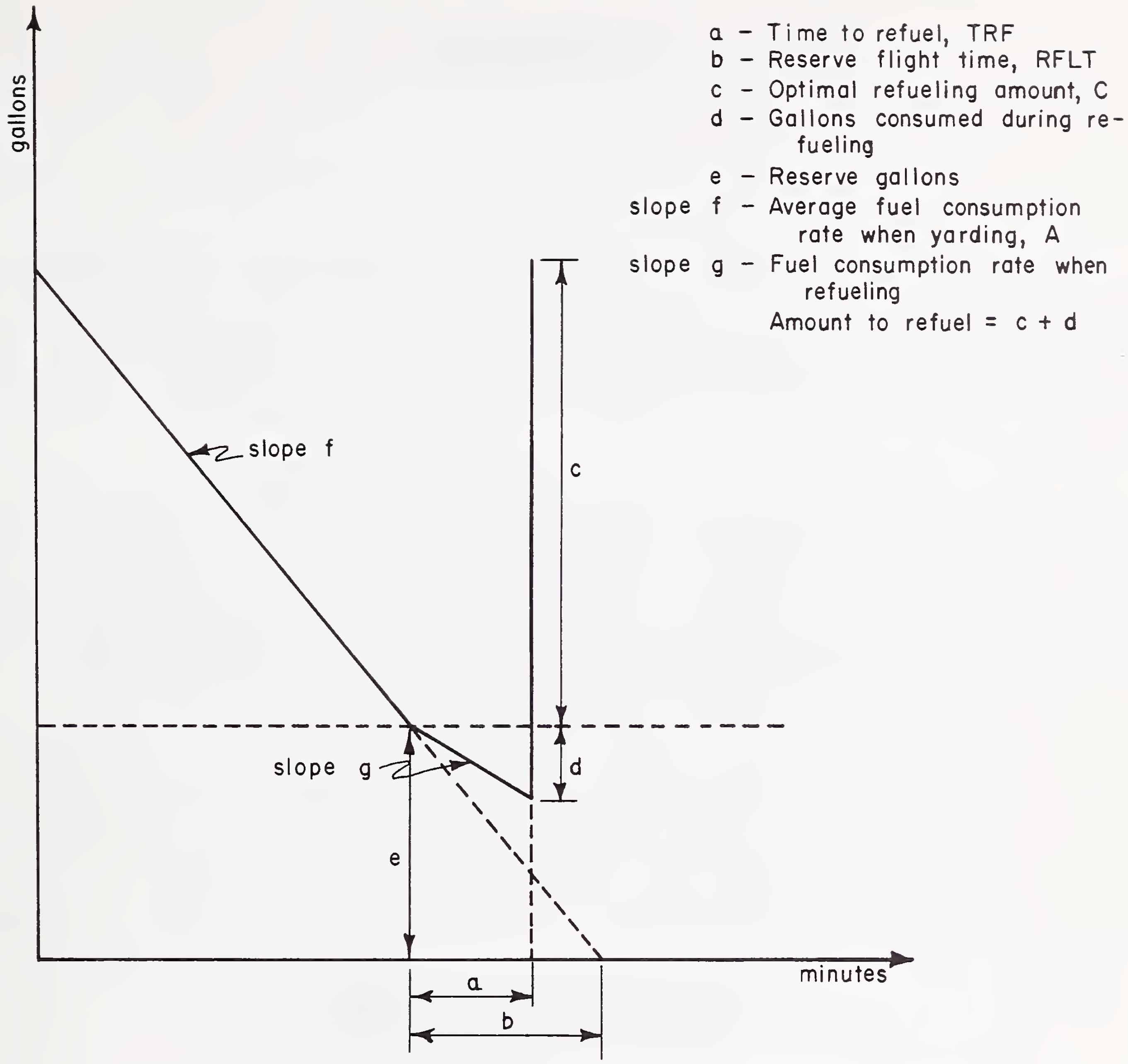


Figure 8.--Calculation of fuel load when helicopter remains running while being refueled.

SUMMARY

Yarding by means of a helicopter has a number of advantages, notably minimal environmental impact and the capability to harvest otherwise inaccessible timber. A helicopter logging operation is fairly expensive; because of this, thorough planning and control efforts are more imperative than for conventional logging methods. The cost effectiveness of a helicopter logging operation is very sensitive to parameters of and decisions pertaining to the system. Every effort should be made to maximize efficiency.

The model presented in this paper prescribes within parameters of the system optimal refueling for a helicopter logging operation. The model has been programed in FORTRAN IV and is well documented. Several features have been incorporated in the program to permit the user to accomplish alternative evaluations. Effects of variables such as yarding distance, location of the landing, flight load factor, costs, and others can easily be assessed. The model can also be used to predict production under given circumstances and can be used as a benchmark for monitoring production.

LITERATURE CITED

Binkley, Virgil W.
1972. Helicopter logging with the S64E skycrane: report of sale. USDA For. Serv., Pac. Northwest Reg., Timber Manage., 23 p.

Stevens, P. M.
1972. Helicopter technical summary: FALCON report. The Aerospace Corp., San Bernardino Oper. Rep. ATR-72(S7266)-1, 37 p.

Stevens, Paul M.
1973. Economic and safety aspects of helicopter logging: FALCON report. The Aerospace Corp., USDA For. Serv., PNW Grant 9, 37 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1974 — 677-087 / 2 REGION NO. 8

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)